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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(54) Title: ACTIVE INTERPHASE REACTOR FOR 12-PULSE RECTIFIER
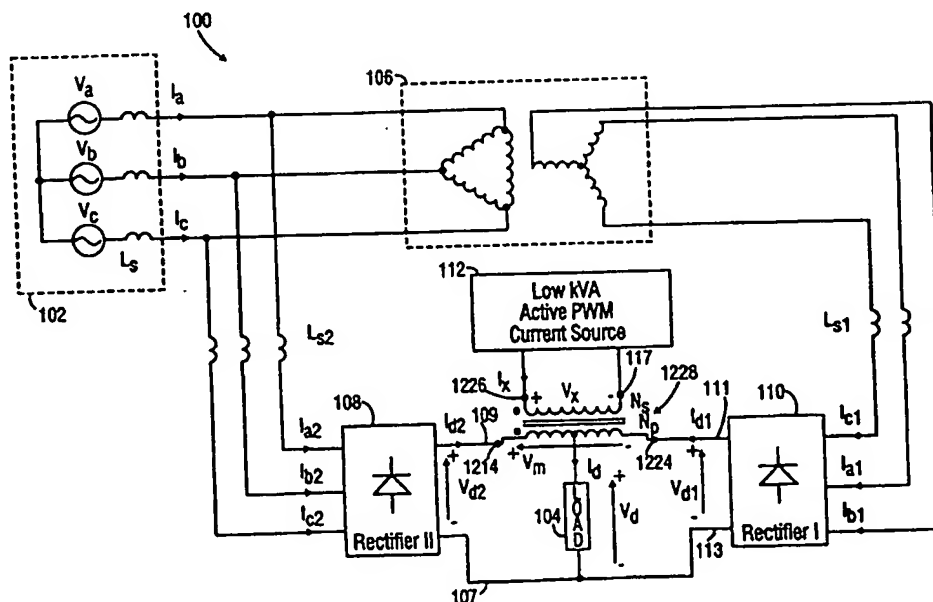
(57) Abstract

An active interphase reactor for twelve-pulse diode rectifiers is disclosed. The system draws near sinusoidal currents from a power utility. In one embodiment, a low kVA (0.02 P_o (PU)) active current source injects a triangular current into an interphase reactor of a twelve-pulse diode rectifier. This modification results in near sinusoidal utility input currents with less than 1 % THD. In alternative embodiments, a low kVA, 12-pulse system with an autotransformer arrangement (kVA rating of 0.18 P_o (PU)) is implemented with the proposed active interface reactor. The resulting systems draw clean power from the utility and are suitable for powering larger kVA ac motor drive systems.

ACTIVE INTERPHASE REACTOR FOR 12-PULSE RECTIFIER

FIELD OF THE INVENTION

This invention relates generally to the field of electric power systems, and more particularly to an interface to an electric utility.

BACKGROUND OF THE INVENTION

Large harmonics, poor power factor, and high total harmonic distortion (THD) in a utility (power supply) interface are common problems when nonlinear loads such as adjustable speed drives, power supplies, induction heating systems, UPS systems and aircraft converter systems are connected to the electric utility.

In some systems, the interface to the electric utility includes a three phase uncontrolled diode bridge rectifier. Due to the nonlinear nature of some loads, the input line currents can have significant harmonics. For adjustable speed AC motor drive systems with no DC-link smoothing inductor, the discontinuous conduction of the diode bridge rectifier can result in high current THDs which can lead to the malfunction of other sensitive electronic equipment.

One recommended practice to address these issues, IEEE 519, has evolved to maintain utility power quality at acceptable levels. ·See, "IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems", *IEEE PES and Static Converter Committee of IAS*, Jan. 1993.

A number of methods have been proposed to overcome the presented problems. See, e.g., J. Schaefer, "Rectifier Circuits: Theory and Design," John Wiley & Sons, Inc., 1965; B. R. Pelly, "Thyristor Phase-Controlled Converters and Cycloconverters, John Wiley & Sons, 1971; R. W. Lye, etc. al, " Power Converter Handbook," Power Delivery Department, Canadian General Electric Company Ltd., 1976; G. Seguier, "Power Electronic Converters AC/DC Conversions," McGraw-Hill, New York, NY, 1986; G. Oliver, etc. al, "Novel Transformer Connection to Improve Current Sharing on High Current DC Rectifiers," *IEEE IAS Conf.*, 1993, pp. 986-992; S. Miyairi, etc. al, "New Method for Reducing Harmonics Involved in Input and Output of Rectifier with Interphase Transformer," *IEEE Trans. on Industry Applications*, Vol. IA-22, No. 5, Sep./Oct. 1986, pp. 790-797; A. R. Prasad, P. D.

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Ziogas, S. Manias, "An Active Power Factor Correction Technique for Three-Phase Diode Rectifiers," *IEEE Trans. on Power Electronics*, Vol. 6, No. 1, Jan. 1991, pp. 83-92; Ned Mohan, "A Novel Approach to Minimize Line-Current Harmonics in Interfacing Renewable Energy Sources with 3-Phase Utility Systems," *IEEE APEC Annual Meeting*, 1992, pp. 852-858; S. Kim, P. Enjeti, P. Packebush and I. Pitel, "A New Approach to Improve Power Factor and Reduce Harmonics in a Three-Phase Diode Rectifier Type Utility Interface," *IEEE Trans. on Industry Applications*, Vol. 30, No. 6, Nov./Dec. 1994, pp. 1557-1564; I. Pitel and S. N. Talukdar, "A Review of the Effects and Suppression of Power Converter Harmonics," *IEEE IAS Conference*, May 1977; S. Choi, P. Enjeti, I. Pitel, "New Polyphase Transformer Arrangements with Reduced kVA Capacities for Harmonic Current Reduction in Rectifier Type Utility Interface," *IEEE PESC Conf.*, 1995, pp. 353-359; D.A. Paice, "Power Electronic Converter Harmonics: Multipulse Methods for Clean Power," New York: IEEE Press, 1996.

One approach is to use a conventional twelve-pulse diode rectifier which requires two six-pulse diode rectifiers connected via Y-Δ and Y-Y isolation transformers. An interphase reactor is required to ensure the independent operation of the two parallel-connected three-phase diode bridge rectifiers. The operation of the conventional twelve-pulse diode rectifier results in the cancellation of the 5th and 7th harmonics in the input utility line currents.

To increase the pulse number further to 18 or 24, additional diode bridge rectifiers along with complicated multiphase transformer arrangements become necessary, undesirably adding to the cost and complexity of the overall system.

SUMMARY OF THE INVENTION

The present invention relates to a three-phase diode rectifier system which draws substantially sinusoidal input currents from the three phase electric utility. In one embodiment, a Δ-Y isolation transformer of 0.52 P_o (PU) capacity is employed. The interphase reactor and the line impedances L_{s1} and L_{s2} are designed such that stable twelve-pulse operation is obtained with equal current sharing. A low kVA (0.02 P_o (PU)) PWM-controlled active current source injects a compensation current I_x into the secondary winding

of the interphase reactor. The shape of I_x can be computed to alter the utility line current I_a to a perfect sine wave. An approximation to the exact waveshape of I_x is a triangular wave. Therefore, by injecting a triangular shaped current I_x into the secondary winding of the interphase reactor, near sinusoidal input line currents flow in the utility line with less than 1%

5 THD.

In another embodiment, an autotransformer is employed to obtain 30 degree phase shift between the two diode rectifiers. Two interphase reactors now become necessary due to the absence of electrical isolation. The kVA rating of the proposed autotransformer is 0.18 P_o (PU). With the active interface reactor installed, the resulting input current with this approach

10 is also substantially sinusoidal, providing a clean power utility interface.

The various embodiments of the invention result in high performance with reduced kVA components and offer clean power utility interface suitable for powering larger kVA ac motor drives and power electronic systems.

In accordance with one aspect of the invention, a low kVA (0.02 pu) triangular current

15 injected into the secondary winding of the interface reactor results in less than 1% THD in utility line currents, satisfying clean power requirements.

In accordance with another aspect of the invention, the active current source can be configured with low cost, high current, and low voltage single phase half/full bridge MOSFET devices. Also, the active current source electronics (MOSFET's) located at the

20 secondary of the interface reactor are not subjected to utility line disturbances, hence rendering the interface system rugged.

In the event the active current source malfunctions, the elimination of 5th and 7th harmonics is still guaranteed due to 12-pulse operation.

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BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other features and aspects of the present invention will perhaps be best understood with reference to a detailed description of a specific embodiment of the invention, when read in conjunction with the accompanying drawings, wherein:

Figure 1 is a schematic diagram of a power interface system in accordance with one embodiment of the invention;

Figure 2 is a schematic diagram of the system from Figure 1, showing a pulse width modulation current source therein in additional detail;

Figure 3 is a waveform representing the switching function for a rectifier in the system of Figure 1;

Figure 4a is a waveform representing injected current in the system of Figure 1;

Figure 4b is a waveform representing input line current in the system of Figure 1;

Figure 5a is a simulated waveform representing injected current in the system of Figure 1;

Figure 5b is a simulated waveform representing rectifier input current in the system of Figure 1;

Figure 5c is a simulated waveform representing input line current in the system of Figure 1;

Figure 5d is a simulated waveform representing the frequency spectrum of the input current in the system of Figure 1;

Figure 6a is a simulated waveform representing the output voltage of a rectifier in the system of Figure 1;

Figure 6b is a simulated waveform representing the output voltage a second rectifier in the system of Figure 1;

Figure 6c is a simulated waveform representing the voltage across the interphase reactor in the system of Figure 1;

Figure 7 is a schematic diagram of a power interface system in accordance with an alternative embodiment of the invention;

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Figure 8 is a vector diagram of an autotransformer connection in the system of Figure 7;

Figure 9 is a diagram showing currents in the autotransformer windings on a three-limb core of the autotransformer in the system of Figure 7;

Figure 10 is a block diagram of a current controlled pulse width modulation gating signal generator in the system of Figure 7;

Figure 11a is a waveform representing a first rectifier output current in the system of Figure 1;

Figure 11b is a waveform representing a second rectifier output current in the system of Figure 1;

Figure 11c is a waveform representing injected current in the system of Figure 1;

Figure 11d is a waveform representing rectifier input current in the system of Figure 1;

Figure 11e is a waveform representing input line current in the system of Figure 1;

Figure 11f is a waveform representing the frequency spectrum of input current in the system of Figure 1;

Figure 12 is a schematic diagram of a power interface system in accordance with another alternative embodiment of the invention;

Figure 13a is a diagram showing the winding configuration of and currents in two zero sequence blocking transformers in the embodiment of Figure 12; and

Figure 13b is a diagram showing the winding configuration of and currents in an interphase reactor in the embodiment of Figure 12.

DETAILED DESCRIPTION OF SPECIFIC EMBODIMENTS OF THE INVENTION

Referring to Figure 1, there is shown a circuit diagram of a clean power utility interface system 100 in accordance with one embodiment of the invention. As shown in Figure 1, the system 100 is adapted to establish an interface between a three phase power source or power utility 102 and a load 104, and is adapted to shape input line currents denoted I_a, I_b, and I_c in Figure 1. Load 104 may be, for example, but not by way of limitation, a pulse

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width modulated adjustable speed AC/DC motor drive, a switch mode power supply, an induction heating system, or any other power electronic converter which accepts a DC-link voltage.

In the presently disclosed embodiment, a main transformer 106 is provided having delta-wye winding (kVA rating of 0.52 Po (PU)) with a $\sqrt{3}$ to 1 turns ratio to maintain an equal per unit voltage. The windings are connected in such a way as to ensure that two diode bridge rectifiers 108 and 110 have balanced sets of three-phase voltages with 30 degrees of phase shift therebetween.

Each rectifier 108 and 110 is a conventional three-phase diode bridge system adapted to receive a three-phase voltage as input and to derive therefrom a DC output signal presented between positive and negative busses. As such, the details of design and implementation of rectifiers 108 and 110 will not be described herein in detail.

In Figure 1, the three-phase signal applied to rectifier 108 is characterized by the currents I_{a2}, I_{b2}, and I_{c2}, and the DC output from rectifier 108 is characterized by the voltage V_{d2} between the positive and negative outputs 109 and 107 of rectifier 108 and by the current I_{d2} shown in Figure 1 on the positive output from rectifier 108. Likewise, the three-phase signal applied to rectifier 110 is characterized by the currents I_{a1}, I_{b1}, and I_{c1}, and the DC output from rectifier 110 is characterized by the voltage V_{d1} between the positive and negative outputs 111 and 113 of rectifier 110 and by the current I_{d1} shown in Figure 1 on the positive output from rectifier 110. As noted above, transformer 106 is adapted to establish a 30 degree phase shift between the three-phase signal $\{I_{a2}, I_{b2}, I_{c2}\}$ and the three-phase signal $\{I_{a1}, I_{b1}, I_{c1}\}$.

The positive output bus from rectifier 108 is designated with reference numeral 109 and the negative output bus from rectifier 108 is designated with reference numeral 107; that is, the DC output voltage V_{d2} from rectifier 108 is the voltage differential which appears between busses 109 and 107. The positive output bus from rectifier 110 is designated with reference numeral 111 and the negative output bus from rectifier 110 is designated with

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reference numeral 113, so that the DC output voltage V_{d1} from rectifier 110 is the voltage differential which appears between busses 111 and 113.

The utility interface system 100 of Figure 1 corresponds generally to a conventional 12-pulse interface system; however, an interphase reactor 114 in the embodiment of Figure 1 is coupled to a low kVA active pulse width modulation (PWM) current source 112. Current source 112 is adapted to inject a low kVA PWM current into a secondary winding of the interphase reactor 114, in order to shape input line current.

In the presently disclosed embodiment of the invention, interphase reactor 114 is a transformer whose primary winding (corresponding to transformer terminals 1214 and 1224) is disposed between the positive outputs 109 and 111 of the respective rectifiers 108 and 110. Interphase reactor 114 supports the 6th order harmonic voltages and is wound to cancel the DC component of the current produced by rectifiers 108 and 110. In addition, the secondary winding of interphase reactor 114 (corresponding to transformer terminals 1226 and 1228) is coupled between the outputs of the low kVA active pulse width modulation current source 112.

As shown in Figure 1, load 104 is coupled between interphase reactor 114 and the respective negative output busses 107 and 113 of rectifiers 108 and 110. In the presently disclosed embodiment of the invention, load 104 is preferably coupled to the midpoint of the primary winding of interphase reactor 114, such that the current through load 104 is the sum of the output currents I_{d2} and I_{d1}.

With the PWM current source disabled (i.e., with $I_x = 0$) the system 100 operates as a conventional 12-pulse rectifier providing cancellation of the 5th and 7th harmonics in the input line currents, I_a, I_b and I_c. The active current source, when injecting a current I_x into the interphase reactor 114, results in near sinusoidal input current with a unity input power factor.

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Waveforms may be analyzed to determine the relationship between current I_x and input currents I_a, I_b and I_c. With $I_x = 0$, input current I_a can be shown to be given by the following equation:

$$I_a = I_{a2} + \frac{1}{\sqrt{3}}(I_{a1} - I_{c1})$$

(1)

Equation (1) describes a 12-pulse input line current with 5th and 7th harmonics absent and

$$I_{d1} - I_{d2} = \frac{1}{2}I_d$$

(2)

where, as noted above, I_{d1} is the current out of rectifier 110, I_{d2} is the current out of rectifier 108, and I_d is the current through load 104. In accordance with one aspect of the presently disclosed embodiment of the invention, an active current I_x is advantageously injected into the secondary winding 114. Figure 2 shows one circuit topology for implementing this scheme, in particular showing one embodiment of low kVA active PWM current source 112.

Analyzing the MMF relationship in interphase reactor 114 we have,

$$N_p(I_{d2} - I_{d1}) = N_s I_x$$

(3)

where N_p and N_s are the numbers of turns of the primary and the secondary windings of the interphase reactor, respectively. The load current I_d is given by:

$$I_d = I_{d1} + I_{d2}$$

(4)

From Equations (3) and (4) we have:

$$I_{d2} = \frac{1}{2}(I_d + \frac{N_s}{N_p}I_x)$$

(5)

Figure 3 shows switching function S_{a1} (i.e., the normalized function defining conductance of rectifier 110) for phase "a" of rectifier 110 from Figures 1 and 2. The Fourier series expansion for S_{a1} is given by:

$$S_{a1}(t) = \frac{2\sqrt{3}}{\pi}(\sin \omega t - \frac{1}{5}\sin 5\omega t - \frac{1}{7}\sin 7\omega t + \frac{1}{11}\sin 11\omega t + \frac{1}{13}\sin 13\omega t \ldots) \tag{6}$$

and for phases "b" and "c", the switching functions can be written as:

$$S_{b1} = S_{a1}\angle -120^\circ$$
$$S_{c1} = S_{a1}\angle +120^\circ \tag{7}$$

Similarly, the switching functions for rectifier 108 in Figures 1 and 2 with a 30 degree phase shift are:

$$S_{a2} = S_{a1}\angle -30^\circ$$
$$S_{b2} = S_{b1}\angle -30^\circ$$
$$S_{c2} = S_{c1}\angle -30^\circ \tag{8}$$

The input currents for rectifiers 108 and 110 can now be expressed in terms of switching functions as:

$$\begin{bmatrix} I_{a1} \\ I_{b1} \\ I_{c1} \end{bmatrix} = \begin{bmatrix} S_{a1} \\ S_{b1} \\ S_{c1} \end{bmatrix} I_{d1} \tag{9}$$

and

$$\begin{bmatrix} I_{a2} \\ I_{b2} \\ I_{c2} \end{bmatrix} = \begin{bmatrix} S_{a2} \\ S_{b2} \\ S_{c2} \end{bmatrix} I_{d2} \tag{10}$$

Equation (1) can now be modified using Equation (5) and the switching functions described in Equations (6)-(10) as:

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$$I_a = \frac{1}{2\sqrt{3}}(S_{a1} - S_{c1}) \cdot (I_d - \frac{N_s}{N_p}I_x) + \frac{1}{2}S_{a2}(I_d + \frac{N_s}{N_p}I_x) \tag{11}$$

Equation (11) illustrates the relationship between I_x and input current I_a. For input current I_a to be sinusoidal,

$$I_x = \frac{N_p\left[2I_{a,1} - I_d\left(\frac{S_{a1} - S_{c1}}{\sqrt{3}} + S_{a2}\right)\right]}{N_s\left(\frac{S_{c1} - S_{a1}}{\sqrt{3}} + S_{a2}\right)} \tag{12}$$

Note I_a is replaced by $I_{a,1}$,where $I_{a,1}$ is the fundamental rms component of I_a. Therefore, equation (12) describes the exact shape of I_x for a given load current I_d. Since input power is equal to output power, we have

$$\sqrt{3}V_{LL}I_{a,1} = V_dI_d \tag{13}$$

where $V_d = 1.35\ V_{LL}$ and V_{LL} is the line to line rms voltage.

Hence, from Equation (13) we have,

$$I_{a,1} = 0.7794\ I_d \tag{14}$$

For input current I_a to be sinusoidal, i.e., for:

$$I_a = \sqrt{2}\ I_{a,1}\sin\omega t \tag{15}$$

Figure 4a shows the shape of I_x for sinusoidal input current computed from Equations (12) and (15). Figure 4b shows the resultant essentially pure sinusoidal input line current I_a.

From Figure 4a, it is apparent that I_x is substantially triangular in shape. For the purposes of simulating the system 100 of the presently disclosed embodiment, the injected current I_x can be assumed to be a triangular wave shape, as shown in Figure 5a. In

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simulations of the system 100, this injected current yields a near sinusoidal input current I_a, as shown in Figure 5c, the frequency spectrum of line current I_a being shown in Figure 5d.

Furthermore, generating a triangular injection current I_x into the secondary of the interphase reactor can be accomplished by means of a PWM-controlled current source (to be hereinafter described in further detail). Figure 5b shows the input current of the rectifier blocks 108 and 110 as a result of the injected current I_x. Figure 5c shows the input line current

Figures 6a and 6b show the DC output voltages V_{d1} and V_{d2}, respectively of rectifiers 110 and 108. Figure 6c shows the voltage V_m across the primary winding of interphase reactor 114.

It should be noted that the injected active current I_x (Figure 5a), which is triangular in shape, yields near sinusoidal input currents (Figure 5c) of less than 1% THD. The kVA rating of the injected current is small, as will be hereinafter discussed.

The line-to-line rms input voltage V_{LL} and DC output current I_d is assumed to be 1 per unit. The voltage V_m across the interphase reactor 114 (see Figure 1) can be expressed as:

$$V_m = V_{d2} - V_{d1} \tag{16}$$

Figure 6a and 6b show the waveshape of V_{d1} and V_{d2}. Furthermore, V_{d1} can be expressed in Fourier series as:

$$V_{d1} = \sqrt{2}V_{LL}\frac{6}{\pi}\sin\frac{\pi}{6}(1 - \sum_{n=6,12,18,\dots}^{\infty}\frac{2}{n^2-1}\cos\frac{n\pi}{6}\cos n\omega t) \tag{17}$$

Output voltage V_{d2} is phase shifted by 30 degrees. By substituting Equation (17) into Equation (16), V_m can be expressed as:

$$V_m = -5.4018V_{LL}\sum_{n=6,12,18,\dots}^{\infty}\frac{1}{n^2-1}\cos\frac{n\pi}{6}\sin\frac{n\pi}{12}\sin n(\omega t - \frac{\pi}{12}) \tag{18}$$

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From Equation (18), the rms value of V_m can be computed as:

$$V_{m,rms} = 0.1098 \, V_{LL} \tag{19}$$

The voltage V_x across the interphase reactor secondary winding is given by,

$$V_x = \frac{N_s}{N_p} V_m \tag{20}$$

Then, from Equations (19) and (20) the rms value of V_x is,

$$V_{x,rms} = 0.1098 V_{LL} \frac{N_s}{N_p} \tag{21}$$

As discussed above, the peak value of the current I_x of Figure 5a is $0.5 I_d$. Therefore, the rms value of I_x for a triangular waveshape is:

$$I_{x,rms} = \frac{0.5}{\sqrt{3}} I_d \frac{N_p}{N_s} = 0.2887 \, I_d \frac{N_p}{N_s} \tag{22}$$

The rms value of I_x can be reduced by adjusting turns ratio (N_p/N_s) between the primary and the secondary windings of the interphase reactor 114.

From Equations (21) and (22), the kVA rating of the injected current source, kVA_{INV}, can be computed as,

$$\begin{aligned} kVA_{INV} &= V_{x,rms} \cdot I_{x,rms} \\ &= 0.0227 P_o (PU) \end{aligned} \tag{23}$$

Equation (23) shows that the kVA rating of the injected current source I_x is a small percentage of the output power. This demonstrates the superior features of the system 100 in accordance with the presently disclosed embodiment of the invention to a realize clean power utility interface.

Referring now to Figure 7, there is shown a circuit diagram of active interphase reactor system 100' in accordance with an alternative embodiment of the invention. It is to be understood that those elements of the system 100' in Figure 7 which are substantially identical to those in the system of Figures 1 and 2 will retain identical reference numerals in Figure 7.

Figure 7 shows the clean power utility interface implementation 100' whose main transformer 700 has an autotransformer connection. The autotransformer configuration shown in Figure 7 does not have ohmic isolation and allows for smaller magnetic sizes. Figure 8 shows the vector diagram of the delta type autotransformer 600. The autotransformer 600 generates two three-phase sets of voltages $\{I_{a1}, I_{b1}, I_{c1}\}$, and $\{I_{a2}, I_{b2},$ and $I_{c2}\}$, displaced ± 15 degrees respectively from the input supply, as shown in the vector diagram of Figure 8.

With continued reference to Figure 7, system 100' in accordance with the presently disclosed embodiment of the invention includes a second interphase reactor 602 disposed between the respective negative busses 107 and 113 of rectifiers 108 and 110, in addition to interphase reactor 114 previously discussed. The autotransformer configuration maintains a virtual ground about the midpoint of rectifiers 108 and 110. This requires application of two interphase reactors 114 and 702. As shown in Figure 7, the respective secondary windings of the first and second interphase reactors 114 and 702, respectively, are coupled in series between the outputs of the low kVA active PWM current source 112, such that the injected compensation current I_x is injected into the secondary windings of both interphase reactors 114 and 702.

In Figure 7, the primary winding of interphase reactor 702 correspond to transformer terminals designated 704 and 708, while the secondary winding corresponds to transformer terminals 710 and 712.

Figure 9 shows the resulting autotransformer winding arrangement on a three-limb core of transformer 600. It has been shown that the kVA rating of the delta type autotransformer 600 is 0.18 Po (PU). Figure 8 shows the vector diagram of the

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autotransformer winding arrangements. The autotransformer terminals a, b, and c are connected to the three phase utility supply 102 (see Figure 7). Each limb of the autotransformer consists of three windings as shown in Figure 9. Two windings are of length k1 and the third winding is of length $\sqrt{3}$. From Figure 8, a value of k1=0.2679 is shown to produce a phase shift of ±15 degrees (Figure 8). The autotransformer connections therefore generate two sets of three phase outputs: {a', b', c'} connected to rectifier 110 and {a'', b'', c''} connected to rectifier 108. The currents {I_{a1}, I_{b1}, I_{c1}} are rectifier 110 input currents and currents {I_{a2}, I_{b2}, I_{c2}} are rectifier 108 currents, respectively.

Referring again to Figure 7, in accordance with the presently disclosed embodiment of the invention, a current source I_x is injected through the series- connected secondary windings of interphase reactors 114 and 602 such that the utility line currents {I_a, I_b, I_c} are substantially sinusoidal in shape. The switching function analysis discussed above can be repeated for the embodiment of Figure 7. Input current I_a can be expressed as:

$$I_a = \frac{N_s}{2N_p} \cdot \left\{ S_{a2} - S_{a1} + 0.1547(S_{c1} - S_{b1} + S_{c2} - S_{b2}) \right\} \cdot I_x + \frac{1}{2} \left\{ S_{a1} + S_{a2} + 0.1547(S_{b1} - S_{c1} + S_{c2} - S_{b2}) \right\} \cdot I_d$$

(24)

For the triangular-shaped injected current I_x of Figure 5a, the input line current I_a, expressed as in Equation (24), also becomes substantially sinusoidal in shape and approximates that shown in Figure 5c.

As noted above, Figure 2 shows the circuit diagram for implementing the proposed active current source 112 in accordance with the presently disclosed embodiments of the invention. Injected current I_x shown in Figure 5a is generated via a current controlled PWM inverter 120 which drives a pair of insulated gate bipolar transistors (IGBTs) 122 and 124 (or similar switching devices, as would be apparent to those of ordinary skill in the art).

A block diagram of the PWM inverter 120 is shown in Figure 10. As shown in Figure 10, inverter 120 comprises an injected current waveform generator or reference generator

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126, which in the presently disclosed embodiment of the invention is an electrical circuit adapted to generate a triangular waveform. The output of waveform generator 126 is multiplied by the load current I_d by analog multiplier 128 to generate the reference current I_x^*.

5   The reference for the injected current (I_x^*) is synchronized with the input voltages and is configured with standard digital logic circuits and phase locked loop electronics. The reference current I_x^* and the feedback current I_x are compared by application to a summing/differencing circuit 130 whose output is applied to an amplifier 132 to generate a current error signal. The current error is then compared to a triangular carrier wave (25kHz)

10   by comparator 134 to generate the PWM gating signals for the inverter switching devices. The carrier wave is generated by carrier wave generator 136. The closed loop operation of this scheme ensures I_x to follow I_x^* to accomplish the clean power characteristics.

Figures 11a through 11f illustrate some experimental results obtained through implementation of a system in accordance with the embodiment of the invention described

15   above with reference to Figures 1 and 2. Figure 11c shows the injected current I_x and Figures 11a and 11b show the resulting rectifier output currents I_{d1} and I_{d2}, respectively. Figure 11d shows the rectifier input current I_{a1}. Finally, the utility input current I_a and its frequency spectrum are shown in Figures 11e and 11f, respectively. These results are similar to the simulation results shown in Figures 5a through 5d. Experimental results show agreement

20   between theory and practice and demonstrate clean power characteristics of the proposed scheme.

Referring now to Figure 12, there is shown a circuit diagram of active interphase reactor system 100" in accordance with another alternative embodiment of the invention. It is to be understood that those elements of the system 100" in Figure 12 which are substantially

25   identical to those in the system of previous embodiments will retain identical reference numerals in Figure 12.

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In system 100'', an autotransformer 700' is employed to obtain 30 degrees phase shift (rather than 15 degrees, as in the embodiment of Figure 7) between diode rectifiers 108 and 110, along with two zero sequence blocking transformers 1202 and 1204. The two zero sequence blocking transformers 1202 and 1204 are built on one core and are shown in more detail in Figure 13a.

Zero-sequence blocking transformers 1202 and 1204 function to block zero-sequence voltage components in the respective outputs of rectifiers 108 and 110. This function enables rectifiers 108 and 110 to operate independently. In addition, as will be appreciated by those of ordinary skill in the art, the addition of the two zero sequence blocking transformers 1202 and 1204 renders the inclusion of interphase reactor 602 from the embodiment of Figure 7 unnecessary.

As shown in Figure 12, the positive output 109 of rectifier 108 is applied to one terminal 1206 of zero sequence blocking transformer 1202, and the negative output 107 of rectifier 108 is applied to another terminal 1208 of zero sequence blocking transformer 1202. A terminal 1210 of zero sequence blocking transformer 1202 is applied to one terminal 1214 of the primary winding of interphase reactor 114, this connection establishing the current path for current designated i_{02} in Figure 12. Another terminal 1212 of zero sequence blocking transformer 1202, the current path for current designated $i_{02'}$, is coupled to a terminal 1216 of zero sequence blocking transformer 1204.

Likewise, the positive output 111 of rectifier 110 is applied to one terminal 1218 of zero sequence blocking transformer 1204, and the negative output 113 of rectifier 110 is applied to another terminal 1220 of zero sequence blocking transformer 1204. A terminal 1222 of zero sequence blocking transformer 1222 is applied to one terminal 1224 of the primary winding of interphase reactor 114, this connection establishing the current path for current designated i_{01} in Figure 12. Another terminal 1216 of zero sequence blocking transformer 1204, the current path for current designated $i_{01'}$, is coupled to terminal 1212 of zero sequence blocking transformer 1202, as noted above.

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The two terminals of interphase reactor's secondary winding are designated 1226 and 1228 in Figure 12.

Figure 13a shows the winding configuration of and currents i_{01}, $i_{01'}$, i_{02} and $i_{02'}$ conducted in zero sequence blocking transformers 1202 and 1204 from Figure 12. Figure 13b shows the winding configuration and currents conducted in interphase reactor 114.

In one implementation of the invention, the kVA rating of the autotransformer 600 in the embodiment of Figure 12 is 0.18 P_O (PU), the ratings of zero sequence blocking transformers 1202 and 1204 are 0.067 P_O (PU), and the rating of interphase reactor 114 is 0.067 P_O (PU), and the rating of PWM current source 112 is 0.094 P_O (PU). With the active interphase reactor 110'' installed, the resulting input current is substantially sinusoidal, providing a clean power utility interface.

From the foregoing detailed description of specific embodiments of the invention, it should be apparent that an active interphase reactor for a twelve-pulse rectifier system has been disclosed. By injecting a low kVA (0.02 P_o (PU)) active current source I_x into the interphase reactor, near sinusoidal input currents with less than 1% THD can be obtained. A low kVA twelve-pulse system with the disclosed active interphase reactor can be implemented with autotransformers. The resultant system is a high performance clean power utility interface suitable for powering larger kVA ac motor drives and a wide variety of power electronic systems.

Although specific embodiments of the invention have been described herein in some detail, it is to be understood that this has been done solely for the purposes of illustrating various features and aspects of the invention, and is not intended to be limiting with respect to the scope of the invention. It is contemplated that various substitutions, alterations, and/or modifications, including but not limited to those design alternatives that may have been

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specifically discussed herein, may be made to the disclosed embodiments without departing

from the spirit and scope of the invention as defined in the appended claims, which follow.

CLAIMS:

1. A utility interface for drawing current from a three-phase electric utility, comprising:

   a transformer, coupled to said three-phase electric utility, for generating first and second three-phase input signals;

5   first and second rectifiers, coupled to said transformer to receive said first and second three-phase input signals, respectively, for rectifying said first and second three-phase input signals and for producing DC output signals between respective positive and negative outputs of said first and second rectifiers;

   an interphase reactor having a primary winding coupled between said respective

10   positive outputs of said first and second rectifiers;

   an active current source, coupled across a secondary winding of said interphase reactor, for injecting a compensation current into said secondary winding.

2. A utility interface in accordance with claim 1, wherein said transformer has a delta-wye winding connected such that said first and second three-phase input signals are balanced

15   with thirty degrees of phase shift therebetween.

3. A utility interface in accordance with claim 1, wherein said injected compensation current is a substantially triangular waveform.

4. A method of drawing substantially sinusoidal input currents from a three-phase power utility, comprising:

20   (a)   coupling a transformer to said power utility to derive first and second three-phase input signals therefrom;

   (b)   applying said first and second three-phase input signals to first and second rectifiers, respectively, to derive first and second DC signals on first and second bus pairs, respectively, each comprising a positive bus and a negative

25   bus;

   (c)   coupling a primary winding of an interphase reactor between said positive busses of said first and second bus pairs;

- 20 -

(d)   injecting a compensation current across a secondary winding of said interphase reactor.

5.   A method in accordance with claim 4, wherein said transformer has a delta-wye winding connected such that said first and second three-phase input signals are balanced with thirty degrees of phase shift therebetween.

6.   A method in accordance with claim 4, wherein said injected compensation current is a substantially triangular waveform.

7.   A utility interface for drawing current from a three-phase electric utility, comprising:

a transformer, coupled to said three-phase electric utility, for generating first and second three-phase input signals;

first and second rectifiers, coupled to said transformer to receive said first and second three-phase input signals, respectively, for rectifying said first and second three-phase input signals and for producing first and second DC output currents between respective positive and negative outputs of said first and second rectifiers;

a first interphase reactor having a primary winding coupled between said respective positive outputs of said first and second rectifiers and having a secondary winding;

a second interphase reactor having a primary winding coupled between said respective negative outputs of said first and second rectifiers and having a secondary winding serially connected to said secondary winding of said first interphase reactor;

an active current source, coupled across said serially-connected secondary windings of said first and second interphase reactors, for injecting a compensation current into said secondary windings.

8.   A utility interface in accordance with claim 7, wherein said transformer has an autotransformer winding configuration such that said first and second three-phase input

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signals are balanced with plus and minus fifteen degrees of phase displacement from said electric utility.

9.   A utility interface in accordance with claim 7, wherein said injected compensation current is a substantially triangular waveform.
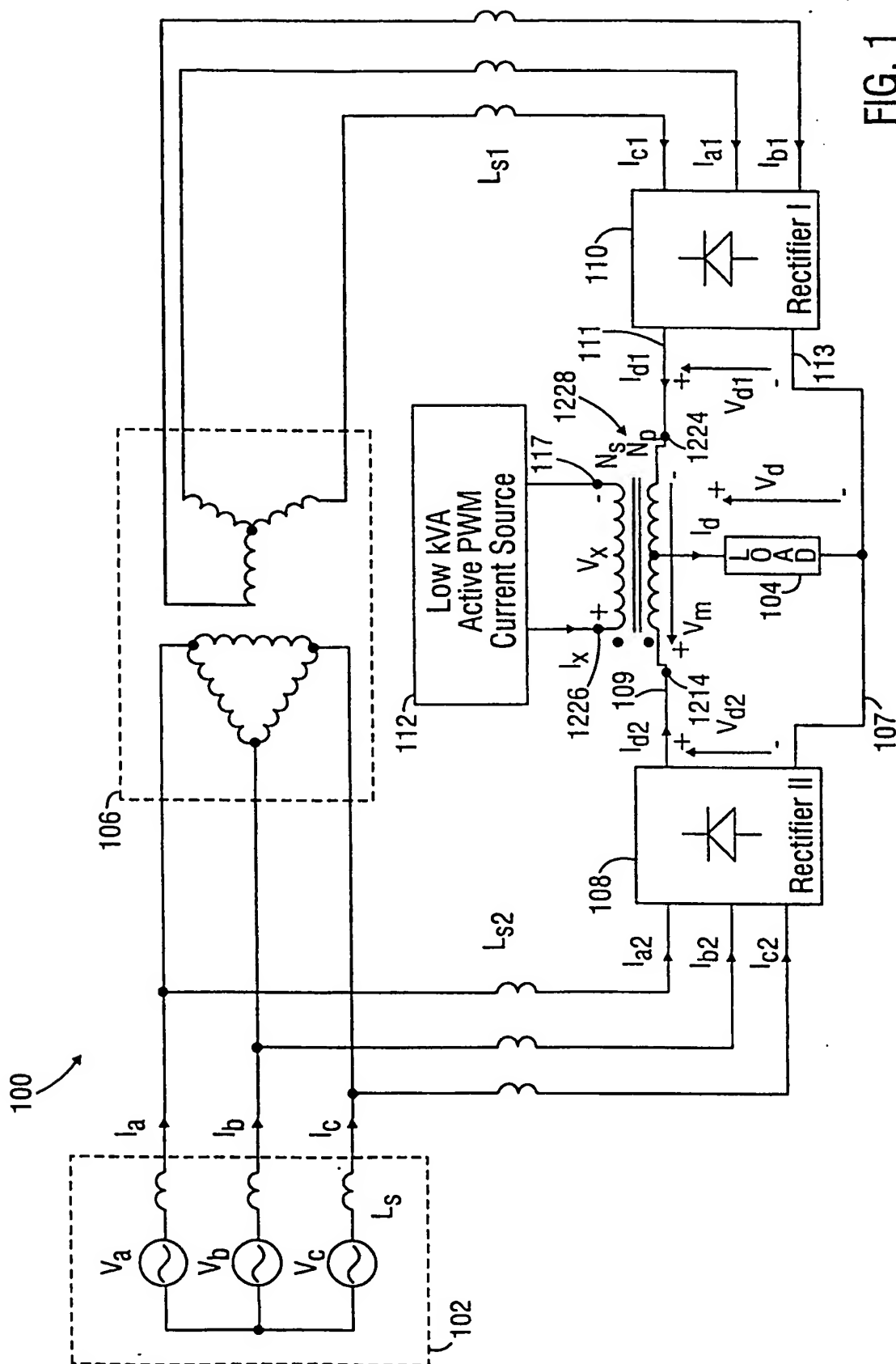
10.   A method of drawing substantially sinusoidal input currents from a three-phase power utility, comprising:

     (a)   coupling a transformer to said power utility to derive first and second three-phase input signals therefrom;

     (b)   applying said first and second three-phase input signals to first and second rectifiers, respectively, to derive first and second DC currents on first and second bus pairs, respectively, each comprising a positive bus and a negative bus;

     (c)   coupling a primary winding of a first interphase reactor between said positive busses of said first and second bus pairs;

     (d)   coupling a primary winding of a second interphase reactor between said negative busses of said first and second bus pairs

     (d)   connecting a secondary winding of said first interphase reactor in series with a secondary winding of said second interphase reactor;

     (e)   injecting a compensation current across said series-connected secondary windings.

11.   A method in accordance with claim 10, wherein said transformer has a delta-wye winding connected such that said first and second three-phase input signals are balanced with thirty degrees of phase shift therebetween.

12.   A method in accordance with claim 10, wherein said injected compensation current is a substantially triangular waveform.
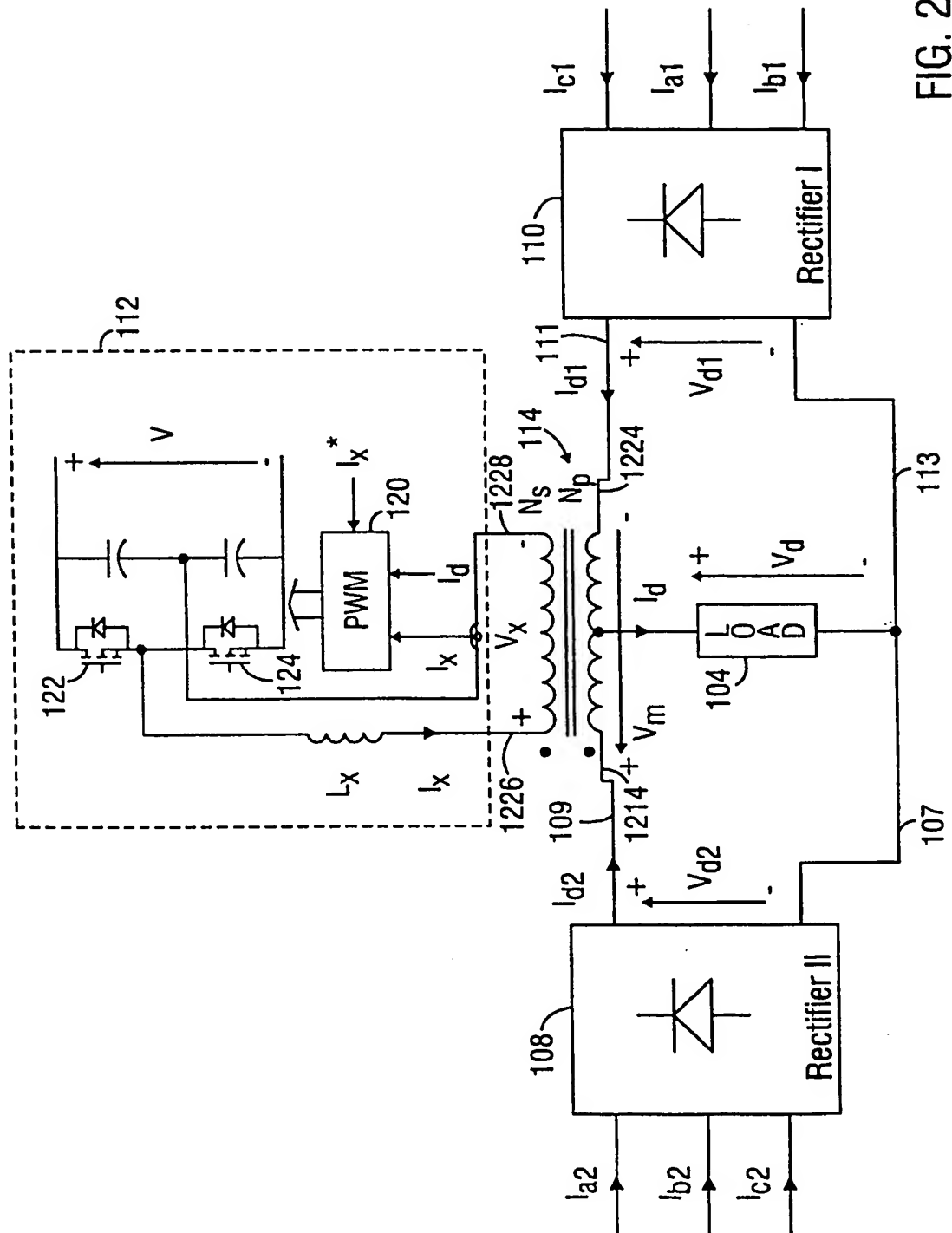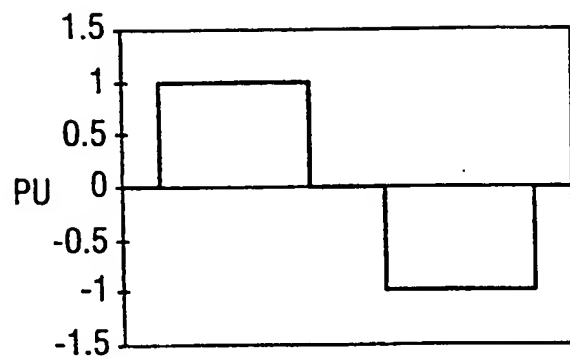
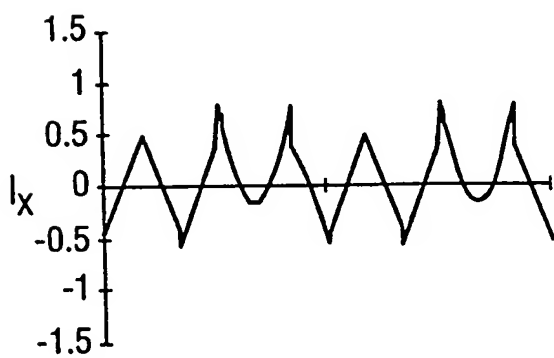13.   A utility interface for drawing current from a three-phase electric utility, comprising:

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a primary transformer, coupled to said three-phase electric utility, for generating first and second three-phase input signals;

first and second rectifiers, coupled to said transformer to receive said first and second three-phase input signals, respectively, for rectifying said first and second three-phase input signals and for producing first and second DC output currents, respectively, between respective positive and negative outputs of said first and second rectifiers;

a first zero sequence blocking transformer having first and second windings each having first and second terminals, said first terminal of said first winding being coupled to said positive output of said first rectifier and said first terminal of said second winding being coupled to said negative output of said first rectifier;

a second zero sequence blocking transformer having first and second windings each having first and second terminals, said first terminal of said first winding being coupled to said positive output of said second rectifier and said first terminal of said second winding being coupled to said negative output of said second rectifier;

said second terminal of said first zero sequence blocking transformer's second winding being coupled to said second terminal of said second zero sequence blocking transformer's second winding;

an interphase reactor having a primary winding coupled between said second terminal of said first zero sequence blocking transformer's first winding and said second terminal of said second zero sequence blocking transformer's first winding, said interphase reactor further having a secondary winding;

an active current source, coupled across said secondary winding of said interphase reactor, for injecting a compensation current into said primary winding of said interphase reactor.

14. A utility interface in accordance with claim 13, wherein said primary transformer has an autotransformer winding configuration such that said first and second three-phase input

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signals are balanced with plus and minus thirty degrees of phase displacement from said electric utility.

15.   A utility interface in accordance with claim 13, wherein said injected compensation current is a substantially triangular waveform.

16.   A method of drawing substantially sinusoidal input currents from a three-phase power utility, comprising:

(a)   coupling a primary transformer to said power utility to derive first and second three-phase input signals therefrom;

(b)   applying said first and second three-phase input signals to first and second rectifiers, respectively, to derive first and second DC currents on first and second bus pairs, respectively, each comprising a positive bus and a negative bus;

(c)   coupling said positive bus and negative bus of said first rectifier to first and second terminals of a first zero sequence blocking transformer;

(d)   coupling said positive bus and negative bus of said second rectifier to first and second terminals of a second zero sequence blocking transformer;

(e)   coupling a primary winding of an interphase reactor between respective third terminals of said first and second zero sequence blocking transformers;

(f)   coupling respective fourth terminals of said first and second zero sequence blocking transformers together,

(g)   injecting a compensation current across a secondary winding of said interphase reactor.

17.   A method in accordance with claim 15, wherein said transformer has a delta-wye winding connected such that said first and second three-phase input signals are balanced with thirty degrees of phase shift therebetween.

18.   A method in accordance with claim 10, wherein said injected compensation current is a substantially triangular waveform.
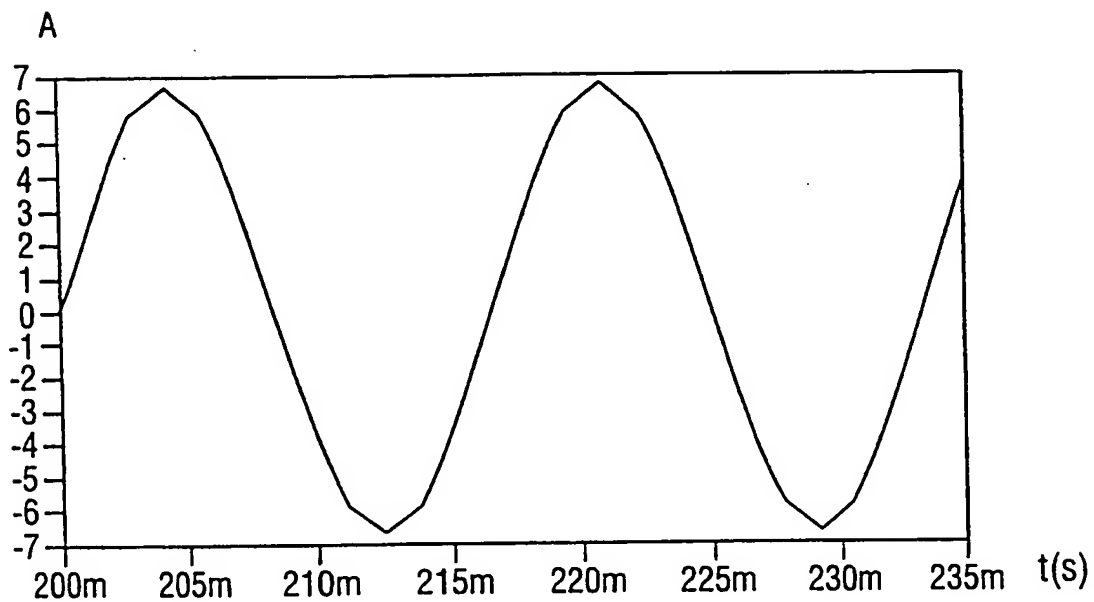
1/15

FIG. 1

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FIG. 2

FIG. 3

FIG. 4A

FIG. 4B

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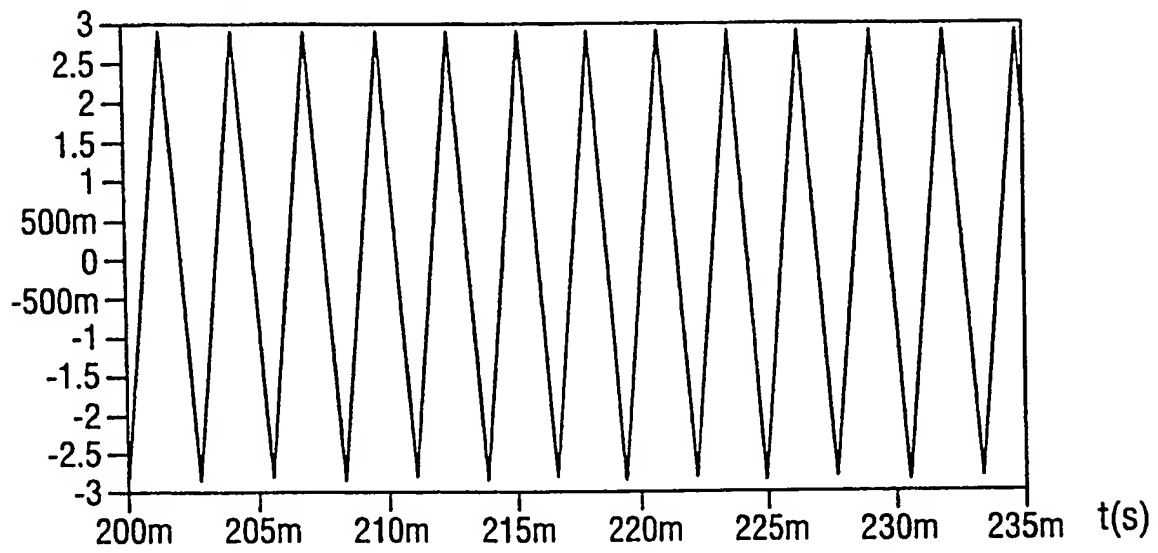
FIG. 5A
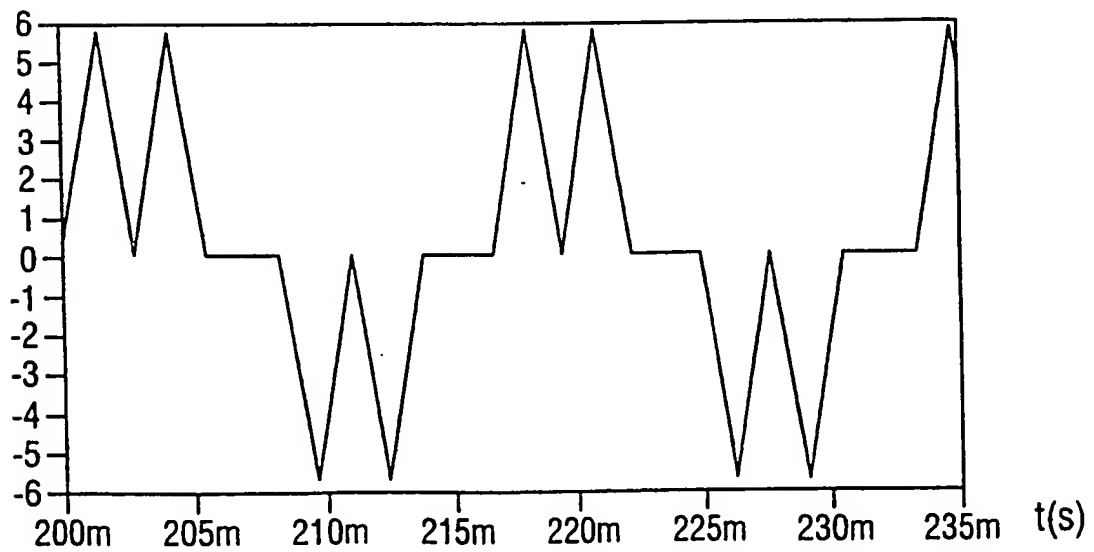
FIG. 5B
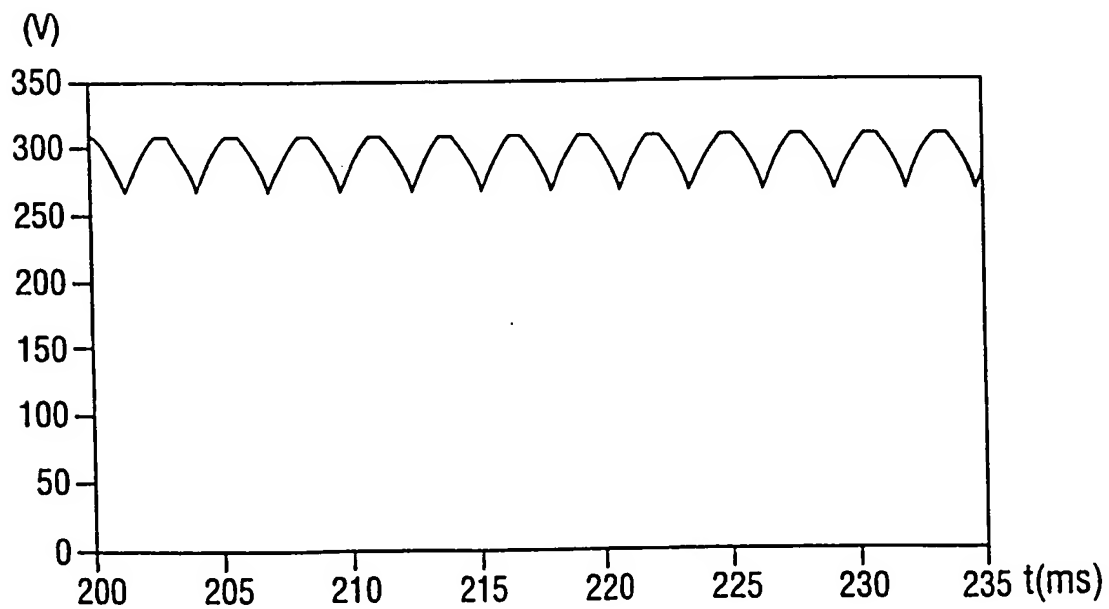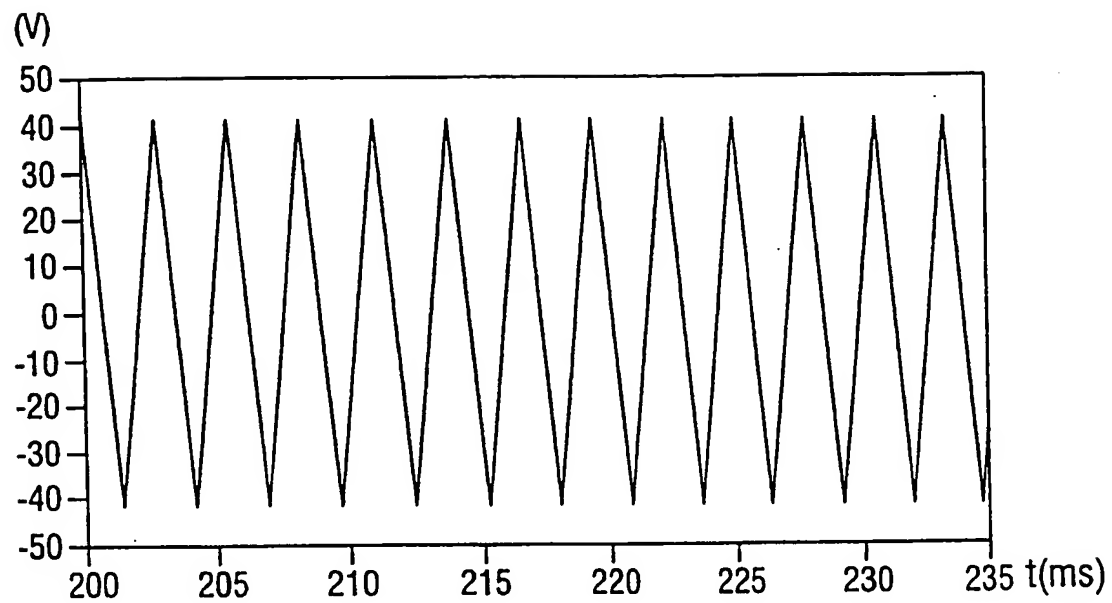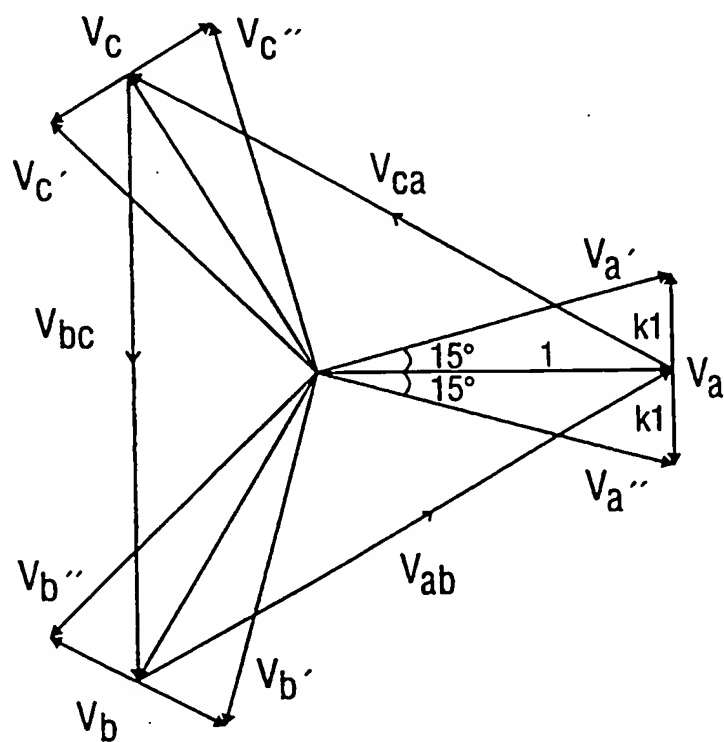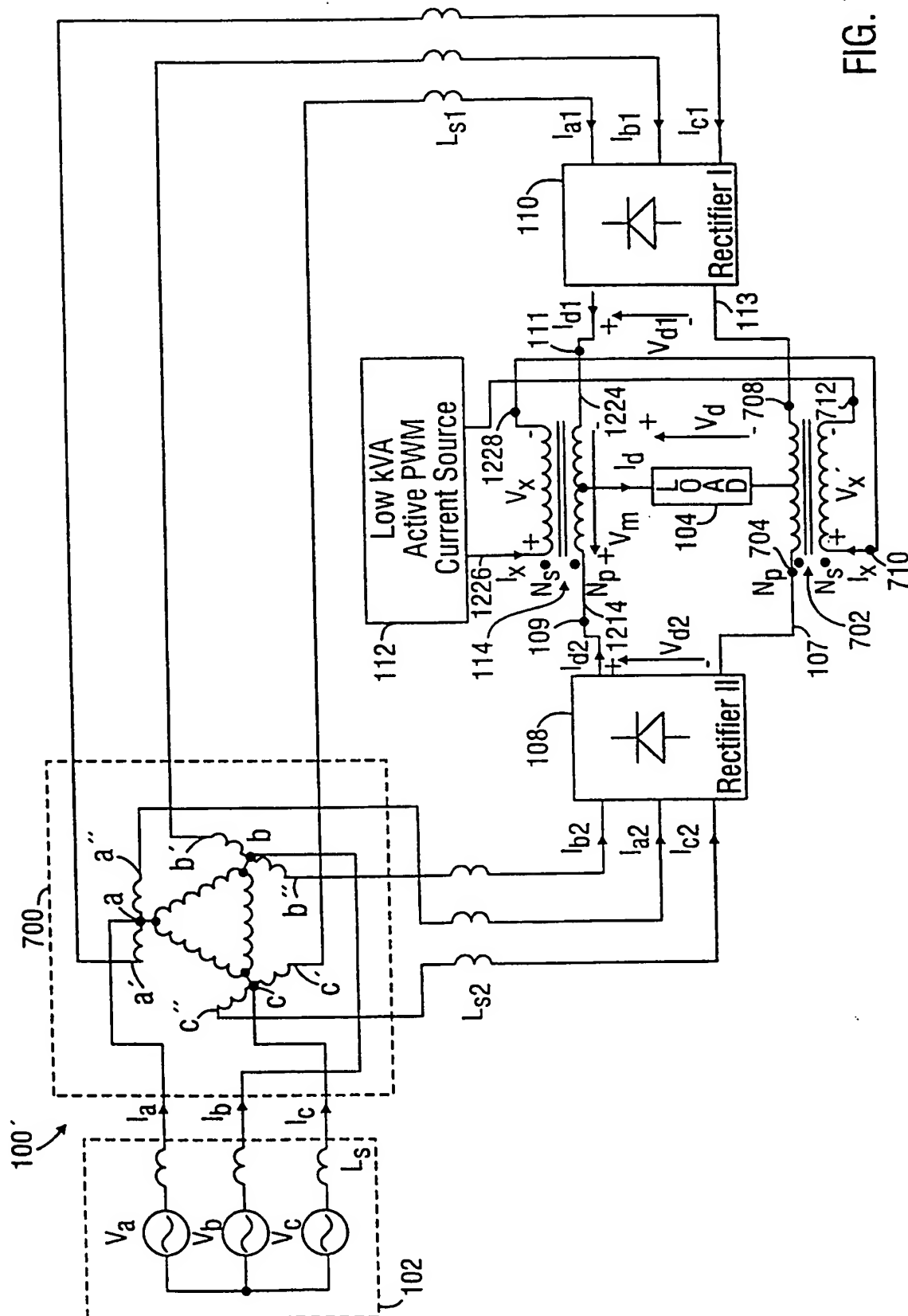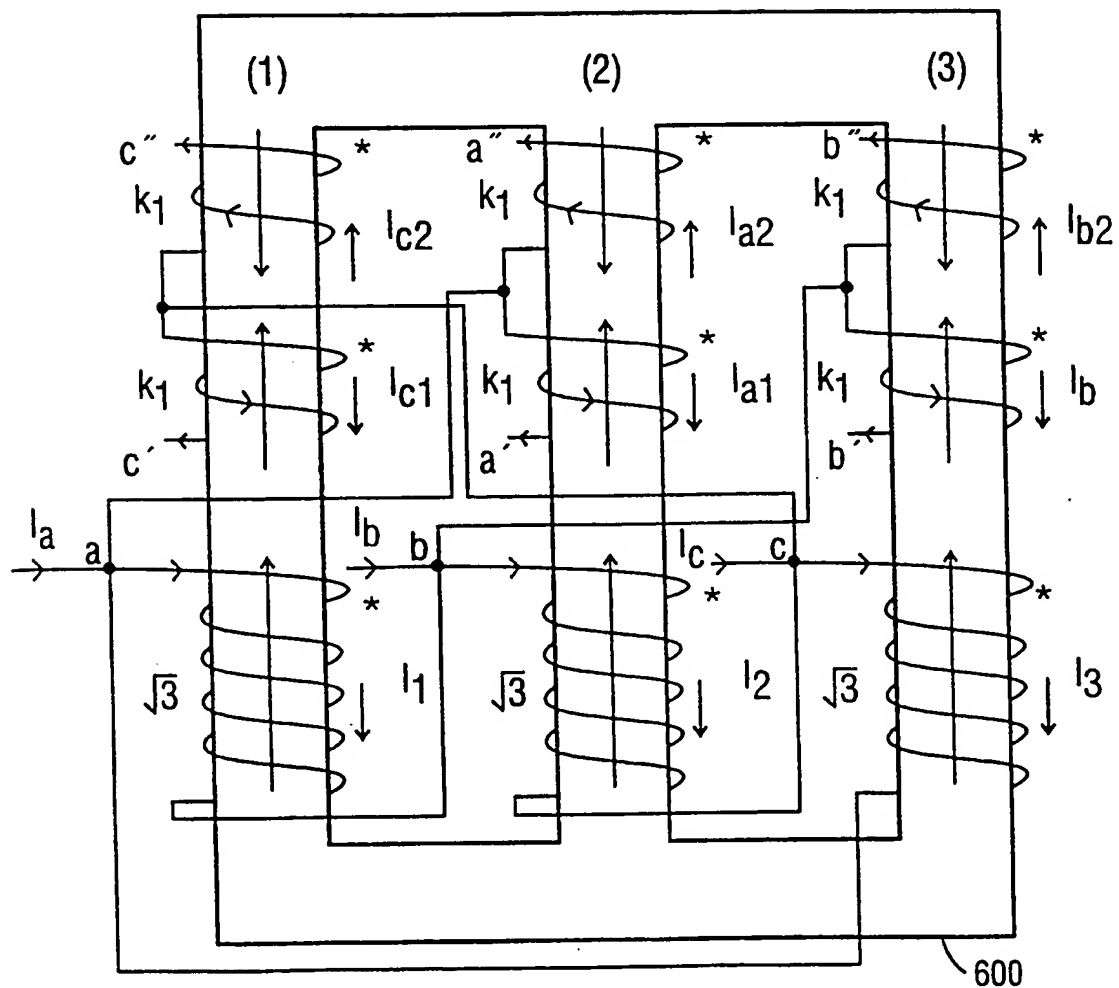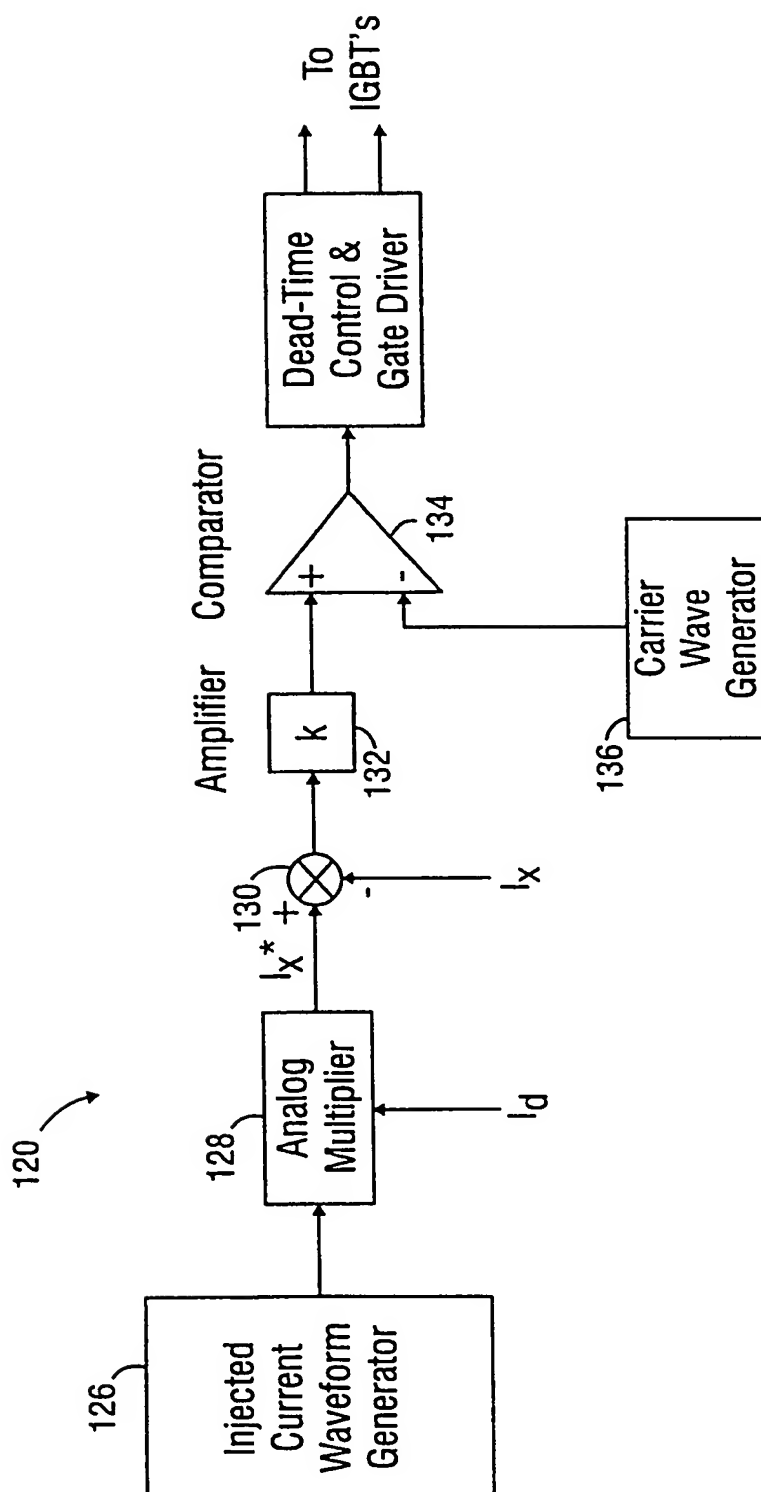
FIG. 5C

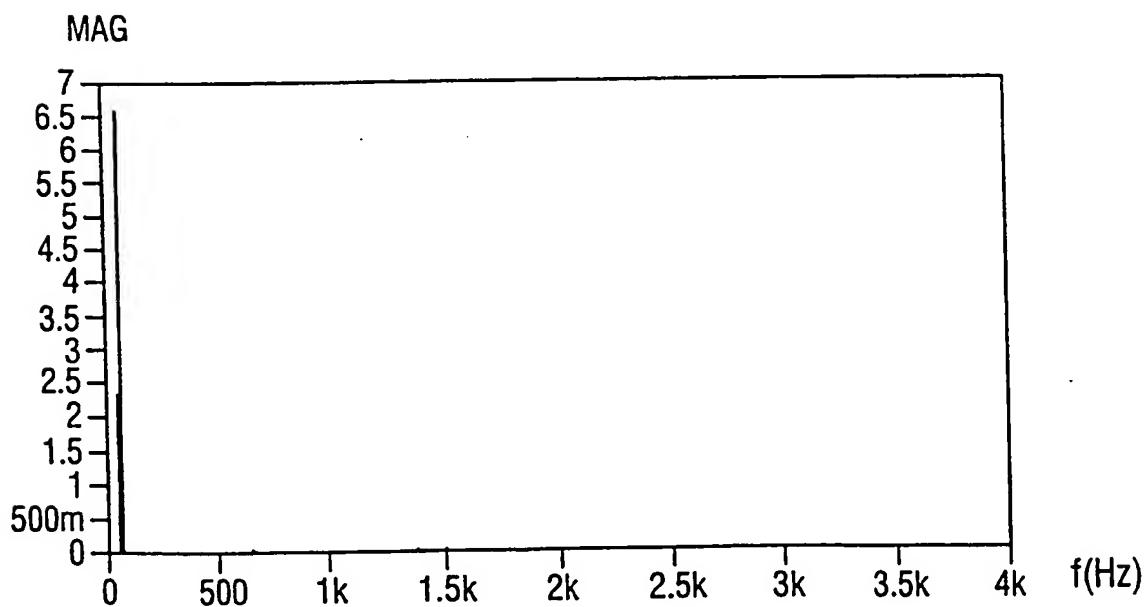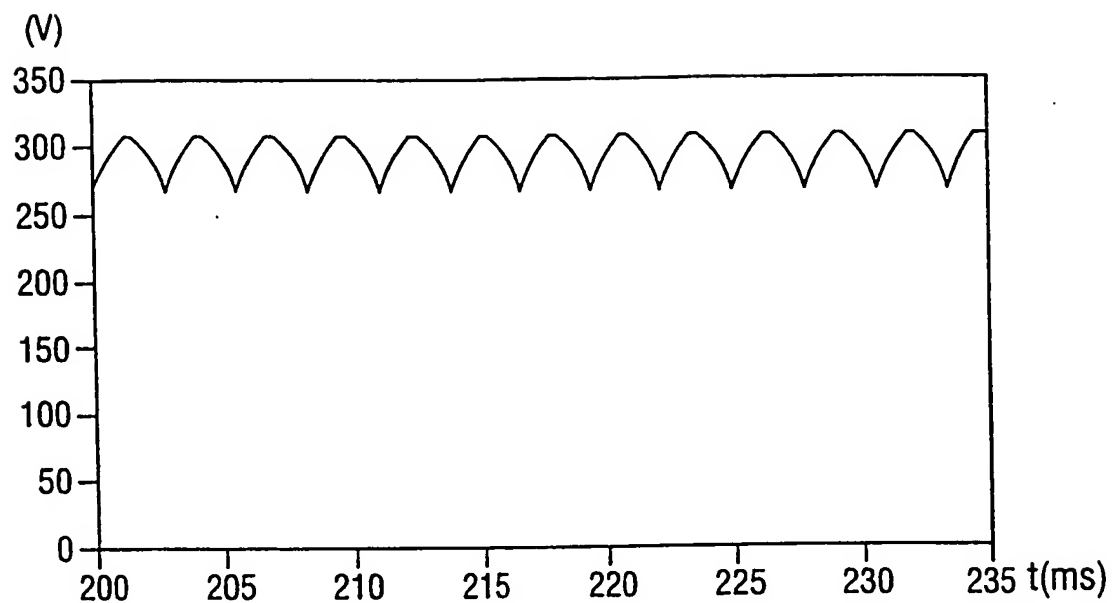FIG. 5D

FIG. 6A

FIG. 6B

FIG. 6C

FIG. 8

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FIG. 7

FIG. 9

To
IGBT's

Dead-Time
Control &
Gate Driver

Comparator

134

Carrier
Wave
Generator

136

Amplifier

k

132

I_x^* 130 +

I_x −
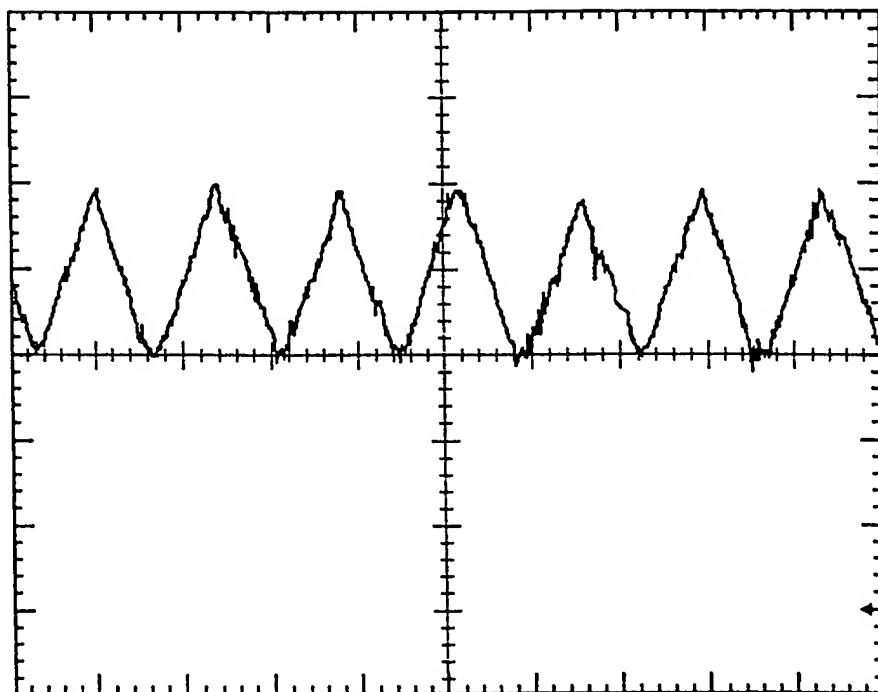
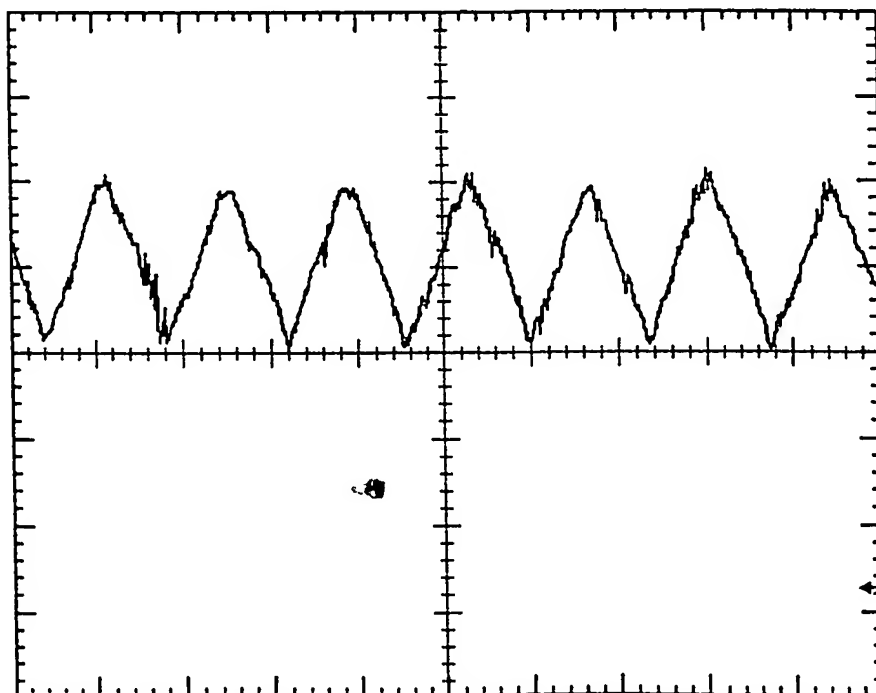Analog
Multiplier

128

I_d

Injected
Current
Waveform
Generator

126

120

FIG. 10
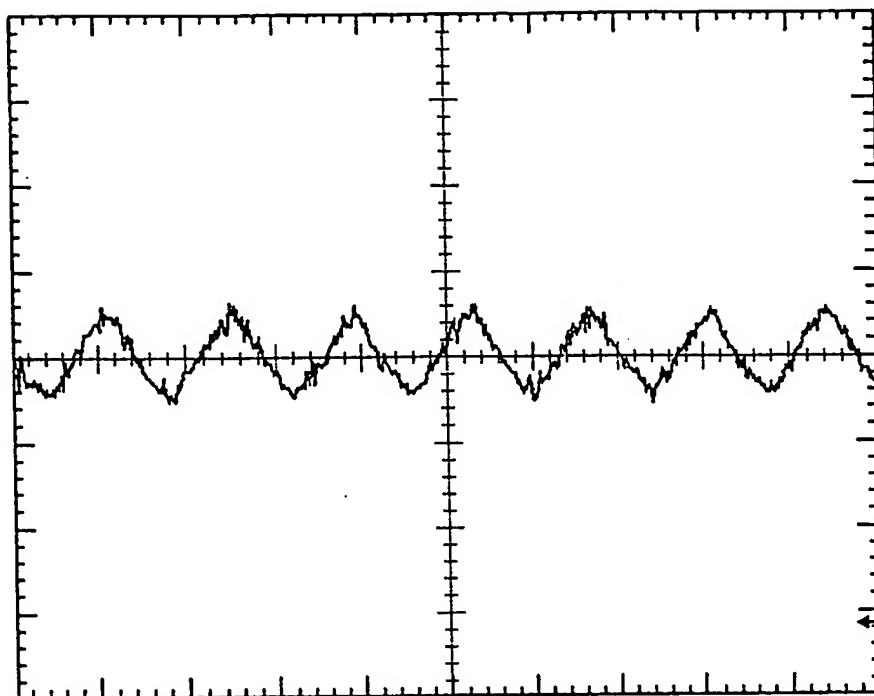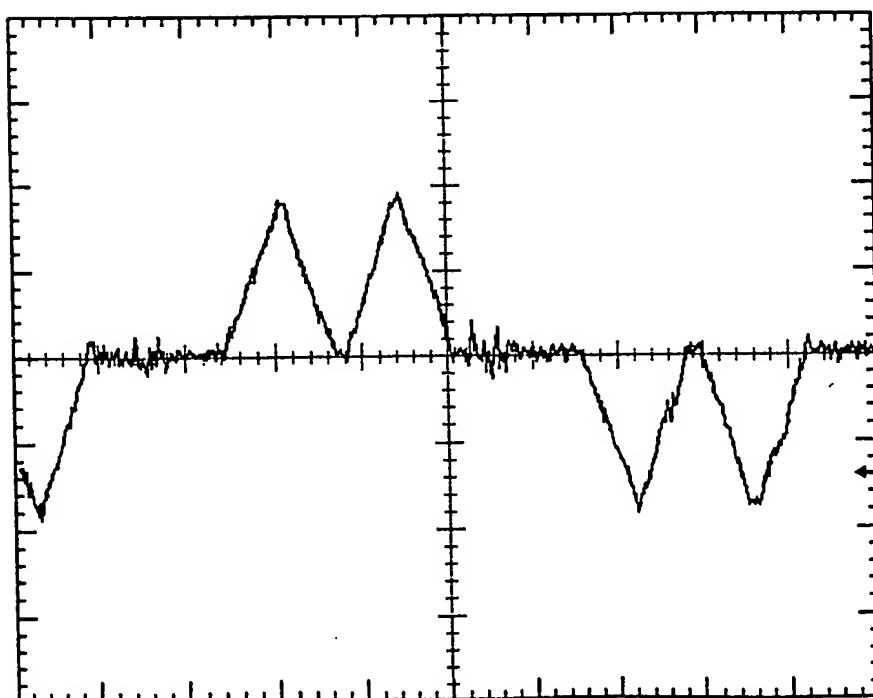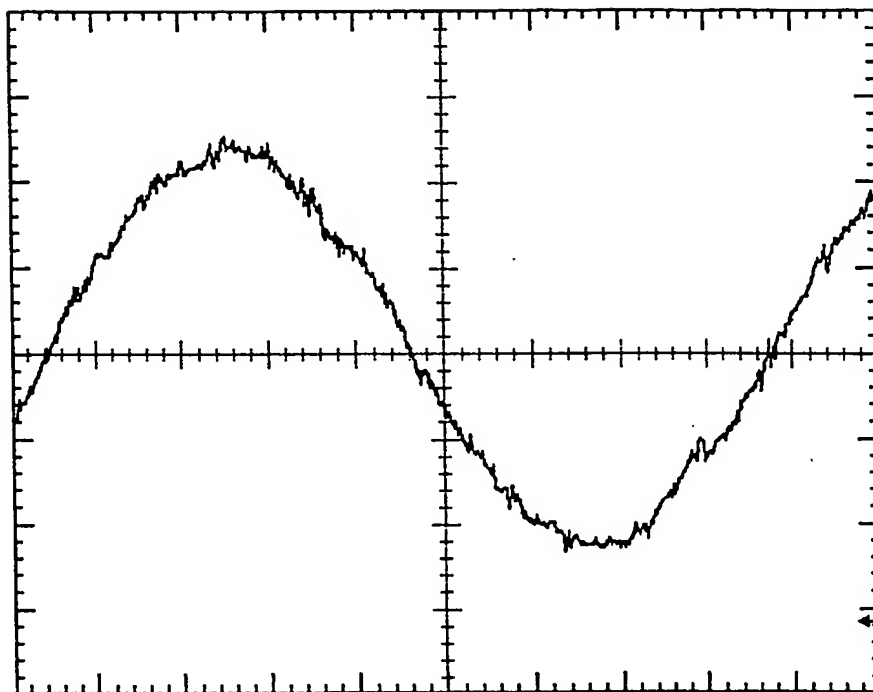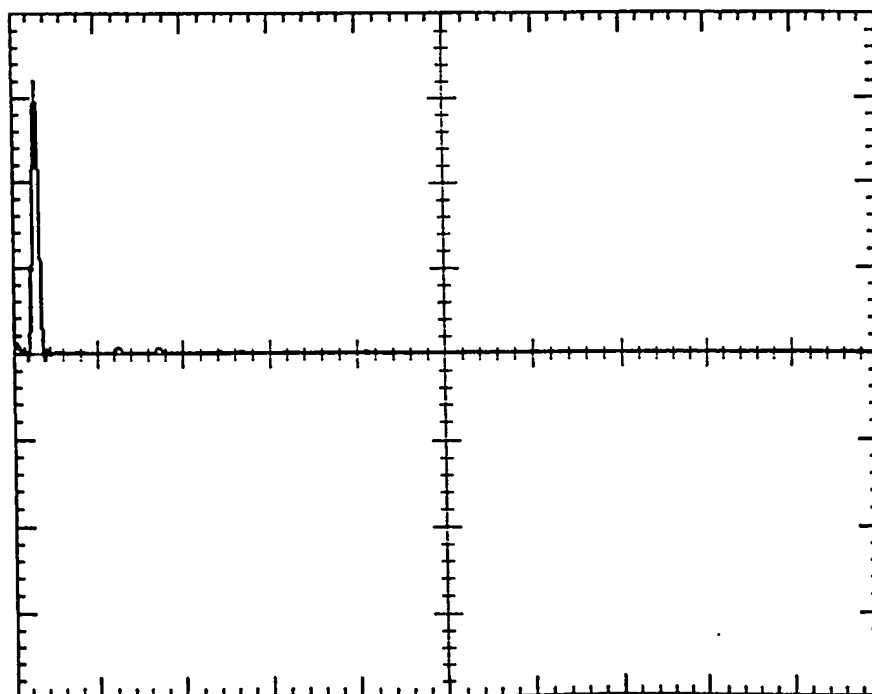
FIG. 11A

FIG. 11B

FIG. 11C

FIG. 11D

FIG. 11E

FIG. 11F

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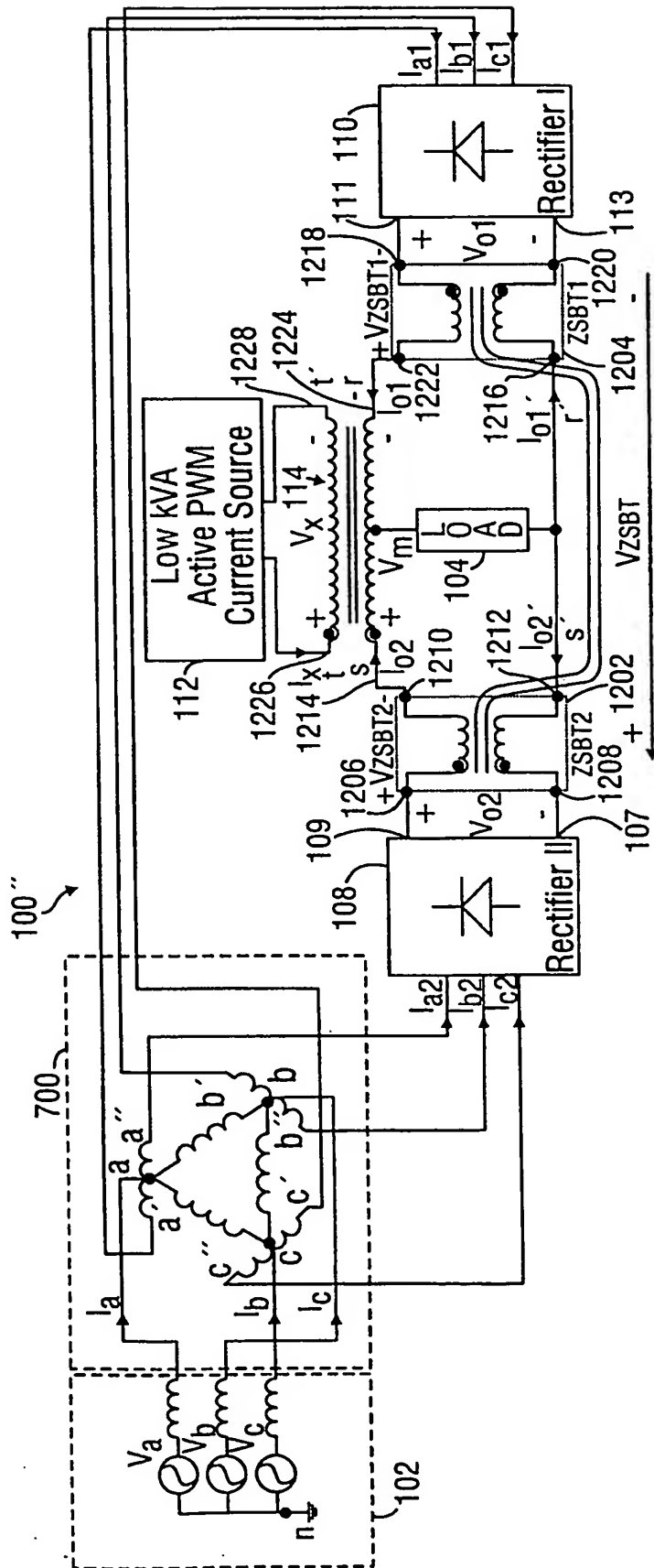
FIG. 12
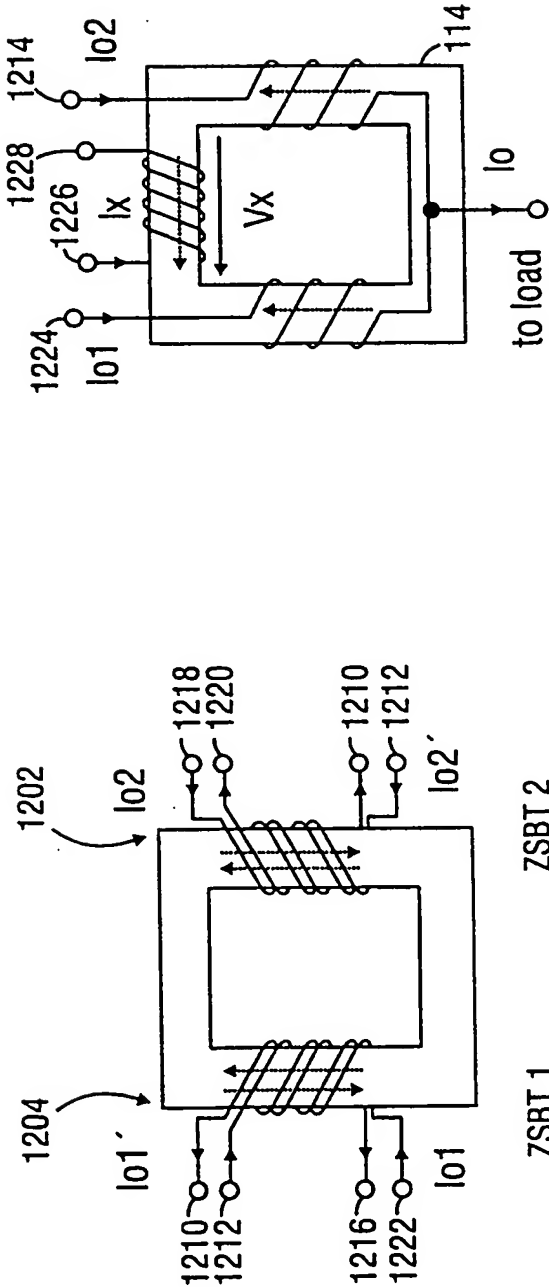
FIG. 13B

FIG. 13A

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6   H02M7/08   H02M1/12

According to International Patent Classification(IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6   H02M

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	CHOI S ET AL: "A NEW ACTIVE INTERPHASE REACTOR FOR 12-PULSE RECTIFIERS PROVIDES CLEAN POWER UTILITY INTERFACE" RECORD OF THE INDUSTRY APPLICATIONS CONFERENCE (IAS), ORLANDO, OCT. 8 - 12, 1995, vol. 3, 8 October 1995, INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, pages 2468-2474, XP000547159 see the whole document ---	1-18
Y	CH 648 965 A (BBC BROWN BOVERI & CIE) 15 April 1985 see abstract; figure 1 ---	1,4
Y	DE 35 45 770 A (LICENTIA GMBH) 25 June 1987 see abstract; figure 1 ---	1,4

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[X] Further documents are listed in the continuation of box C.	[X] Patent family members are listed in annex.

* Special categories of cited documents :

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"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publicationdate of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
27 February 1998	06/03/1998

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Gentili, L

Form PCT/ISA/210 (second sheet) (July 1992)

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category *	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
A	SEWAN CHOI ET AL: "POLYPHASE TRANSFORMER ARRANGEMENTS WITH REDUCED KVA CAPACITIES FOR HARMONIC CURRENT REDEUCTION IN RECTIFIER TYPE UTILITY INTERFACE" RECORD OF THE ANNUAL POWER ELECTRONICS SPECIALISTS CONFERENCE (PESC, ATLANTA, JUNE 12 - 15, 1995, vol. 1, 12 June 1995, INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, pages 353-359, XP000548429 cited in the application see the whole document ---	1-18
A	US 4 739 466 A (GLENNON TIMOTHY F ET AL) 19 April 1988 see abstract; figure 1 -----	1-6

1

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
CH 648965 A	15-04-85	DE 3521519 A	27-02-86
DE 3545770 A	25-06-87	NONE	
US 4739466 A	19-04-88	EP 0297123 A	04-01-89
		WO 8805224 A	14-07-88